CP Violation in B Meson Mixing from Effective Supersymmetric Higgs Bosons

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Outline

- WA, M. Carena, S. Gori, A. de la Puente
  arXiv:1107.3814 [hep-ph]
- WA, M. Carena
  in preparation

B Mixing Basics

Schrödinger equation describing $B_q - \bar{B}_q$ mixing:

$$i\partial_t \begin{pmatrix} B_q(t) \\ \bar{B}_q(t) \end{pmatrix} = \left(M_q + \frac{i}{2}\Gamma_q \right) \begin{pmatrix} B_q(t) \\ \bar{B}_q(t) \end{pmatrix}$$

Three physical parameter:

$$|M_{12}^q| \; , \quad |\Gamma_{12}^q| \; , \quad \phi_q = -\arg\left(\frac{M_{12}^q}{\Gamma_{12}^q} \right)$$

- Γ_{12}^q is dominated by SM tree level decays and hardly affected by NP
- M_{12}^q is loop induced and highly sensitive to NP

$$M_{12}^q = (M_{12}^q)_{\rm SM} \; C_q e^{i\phi_q^{\rm NP}}$$

- C_q constrained by measurements of the mass differences in the B_d and B_s mixing systems: $\Delta M_q = C_q \; \Delta M_q^{\rm SM}$

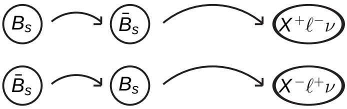
$$0.62 < C_d < 1.15 \quad , \quad 0.79 < C_s < 1.23 \quad @ \; 95\% \text{ C.L.}$$ (Lenz et al. '10)

CPV Observables in B_s Mixing

CP violation in $b \to s$ transitions is predicted to be very small in the SM

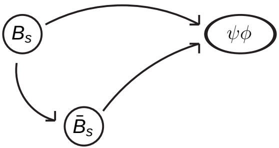
$$\beta_s \sim \text{Arg}(V_{ts}) \simeq 1^\circ \ , \ \phi_s^{\text{SM}} \sim 0.2^\circ \quad \to \quad \text{excellent probe of NP}$$

- semileptonic asymmetry



$$a_{\text{SL}}^s = \frac{\Gamma(\bar{B}_s \to X\ell^+\nu) - \Gamma(B_s \to X\ell^-\nu)}{\Gamma(\bar{B}_s \to X\ell^+\nu) + \Gamma(B_s \to X\ell^-\nu)}$$
$$= \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| \sin(\phi_s^{\text{SM}} + \phi_s^{\text{NP}})$$

- time dependent CP asymmetry in decays to CP eigenstates $B_s \to f$



$$S_f \sin(\Delta M_s t) = \frac{\Gamma(\bar{B}_s(t) \to f) - \Gamma(B_s(t) \to f)}{\Gamma(\bar{B}_s(t) \to f) + \Gamma(B_s(t) \to f)}$$
$$= \sin(2|\beta_s| - \phi_s^{\text{NP}})$$

(model independent correlation between the two observables:
Ligeti, Papucci, Perez ’06; Grossman, Nir, Perez ’09)

like-sign dimuon charge asymmetry at D0

$$A^b_{\mathrm{SL}} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

N_b^{++}: Number of same sign $\mu^+\mu^+$ events from $B \to \mu X$ decays
N_b^{--}: Number of same sign $\mu^-\mu^-$ events from $B \to \mu X$ decays

- Relation to the semileptonic asymmetry

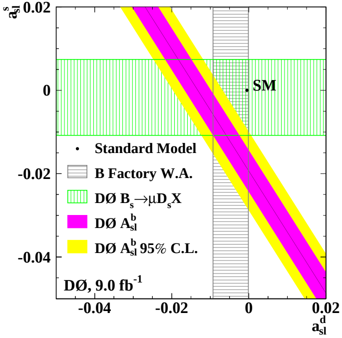
$$A^b_{\mathrm{SL}} = 0.59\, a^d_{\mathrm{SL}} + 0.41\, a^s_{\mathrm{SL}}$$

$$A^b_{\mathrm{SL}}(\mathrm{SM}) = (-0.28 \pm 0.06) \times 10^{-3}$$

(Lenz, Nierste '11)

$$A^b_{\mathrm{SL}}(\mathrm{exp}) = (-7.87 \pm 1.72 \pm 0.93) \times 10^{-3}$$

(D0, arXiv:1106.6308)



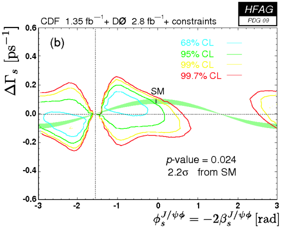
(see talk by M. Williams)

- 3.9σ discrepancy!
- large NP phase in B_s mixing: $\phi_s^{\mathrm{NP}} \simeq -\pi/2$?

Time dependent CP asymmetry in $B_s \to \psi\phi$ at Tevatron

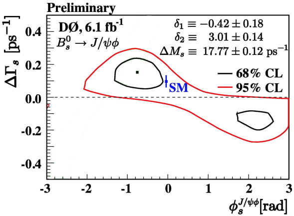
Status 2009

- CDF and D0 analyses seem to hint towards a large negative B_s mixing phase (2-3σ deviation from SM prediction)



The Experimental Situation

Time dependent CP asymmetry in $B_s \to \psi\phi$ at Tevatron



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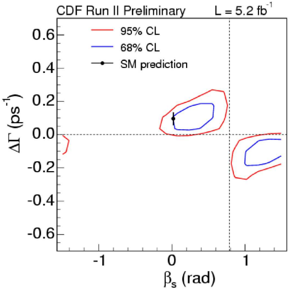


Progress in the last years

- updates from CDF and D0 are in better agreement with the SM ($\simeq 1\sigma$)

  (see talk by J. Martinez Ortega)

The Experimental Situation

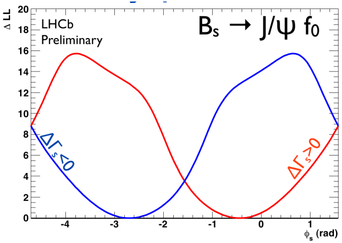
Time-dependent CP asymmetries at LHCb

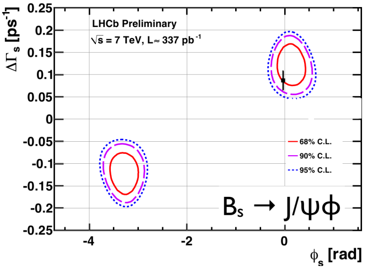
- combination of results on $B_s \to \psi\phi$ and $B_s \to \psi f_0$

$$\phi_s = 0.03 \pm 0.16 \pm 0.07$$

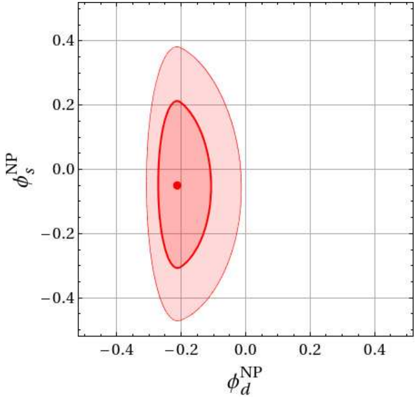
- CP violation in B_s mixing seems SM like!

(LHCb-CONF-2011-056 ,
talk by G. Raven @ Lepton-Photon '11 ,
talk by B. Pietrzyk)





My naive combination



Combining data from

- like-sign dimuon charge asymmetry at D0
- time dependent CP asymmetry in $B_d \to \psi K_s$ from the B factories
- time dependent CP asymmetries in $B_s \to \psi\phi$ and $B_s \to \psi f_0$ from LHCb

- still some room for a NP phase in B_s mixing
- preference towards a non-zero negative NP phase in B_d mixing
  (comes from tensions in the Unitarity Triangle fits
  see e.g. Lunghi, Soni '08,'11; Buras, Guadagnoli '08; Lenz et al. '10)

CP Violation in B Mixing in BMSSM Frameworks

Going Beyond the MSSM

- Lightest Higgs mass above the LEP bound requires heavy stops in the MSSM
  $\rightarrow$ Little Hierarchy Problem: tuning at the % level
- amount of tuning can be reduced with a modified Higgs sector: additional singlets, fat Higgs, λSUSY, ...
- if the mass scale M of the Physics Beyond the MSSM is sufficiently heavy
  $\rightarrow$ description in an effective theory is possible
- there is one unique dim. 5 operator in the super potential that contains only Higgs fields (Dine, Seiberg, Thomas '07)
  (Z: auxiliary spurion that develops an SUSY breaking F-term $Z \rightarrow m_S \theta^2$)

$$\mathcal{L} \supset \frac{\omega}{2M} \int d^2\theta (1 + \alpha Z)(\hat{H}_u \hat{H}_d)^2$$

- Introduces two additional terms in the Higgs potential
  (different structures than the ones present in the MSSM at tree level)

$$V_{\text{Higgs}} = V_{\text{MSSM}} + \left(\frac{\alpha\omega m_S}{2M} (H_u H_d)^2 - \frac{\omega\mu}{M} (H_u H_d)(H_u^\dagger H_u + H_d^\dagger H_d) \ + \ h.c. \right)$$

Effect on the Higgs Spectrum

Complex α and ω $\to$ mixing between scalar and pseudoscalar Higgs bosons

$$\mathcal{M}_H^2 = \begin{pmatrix} M_h^2 & 0 & M_{hA}^2 \\ 0 & M_H^2 & M_{HA}^2 \\ M_{hA}^2 & M_{HA}^2 & M_A^2 \end{pmatrix} \quad , \qquad \begin{aligned} M_{hA}^2 &\simeq v^2 \tfrac{|\omega|\mu}{M} \sin(\phi_\omega + \theta) \\ M_{HA}^2 &\simeq -\tfrac{v^2}{2} \tfrac{|\alpha\omega| m_S}{M} \sin(\phi_\alpha + \phi_\omega + 2\theta) \end{aligned}$$

- all three neutral Higgs bosons can couple significantly to gauge bosons
- significant enhancement of the lightest Higgs mass possible for moderate $\tan\beta$

$$\delta M_{H_1}^2 \simeq \frac{4v^2}{\tan\beta} \frac{|\omega|\mu}{M} \cos(\phi_\omega + \theta) + \ldots$$

- mass splitting between the two heavy Higgs bosons

$$M_{H_3}^2 - M_{H_2}^2 \simeq v^2 \frac{|\alpha\omega| m_S}{M}$$

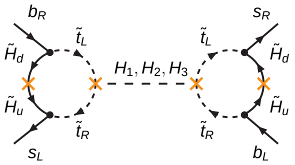
$\to$ can lead to a very interesting Higgs collider phenomenology

WA, Carena, Gori, de la Puente ’11 and talk by A. de la Puente

(see Carena, Ponton, Zurita ’10 for the CP conserving case)

Double Higgs Penguin Contributions to B Mixing

- We assume a Minimal Flavor Violating soft-sector
  $\leftrightarrow$ no sources of flavor violation apart from the SM CKM matrix
- sizable contributions to B mixing can come from double Higgs penguins in the large $\tan\beta$ regime (Buras, Chankowski, Rosiek, Slavianowska '01)



$$\propto \frac{\alpha^3}{4\pi}\frac{1}{M_A^2}(V_{tb}V_{ts}^*)^2\frac{m_b m_s}{M_W^2}\tan^4\beta\frac{|\mu A_t|^2}{\tilde{m}^4}$$

- same contribution as in the MSSM (corrected at the 1/M level)
- only relevant in B_s mixing
- sensitivity to phases of MSSM parameters only through higher order $\tan\beta$ resummation factors
  (Carena, Menon, Noriega-Papaqui, Szynkman, Wagner '06
  Hofer, Nierste, Scherer '09, Dobrescu, Fox, Martin '10)

$$\tan\beta \to \frac{\tan\beta}{1+\epsilon_b\tan\beta}$$

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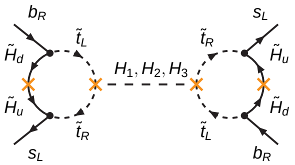
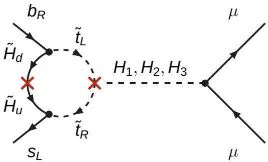


$$\propto \frac{\alpha^3}{4\pi}\frac{1}{M_A^2}(V_{tb}V_{ts}^*)^2\frac{m_b^2}{M_W^2}\tan^4\beta\frac{(\mu A_t)^2}{\tilde{m}^4}\frac{\alpha\omega m_S}{M}\frac{v^2}{M_A^2}$$

- enhanced by m_b/m_s
- mainly relevant for low heavy Higgs masses $M_A^2 \sim v^2$
- directly sensitive to the phases of μA_t and $\alpha\omega$
- comparable contributions to B_s and B_d mixing
- main qualitative difference between the MSSM and the BMSSM in the flavor sector

- Higgs Penguins also contribute to $B_s \to \mu^+\mu^-$
- same contribution as in the MSSM (corrected at the 1/M level)



$$\sim \frac{\alpha_2}{4\pi} \frac{1}{M_A^2} V_{tb} V_{ts}^* \frac{m_b m_\mu}{M_W^2} \tan^3\beta \frac{A_t \mu}{\tilde{m}^2}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{exp}} < 1.1 \times 10^{-8} \quad \text{(LHCb + CMS)}$$

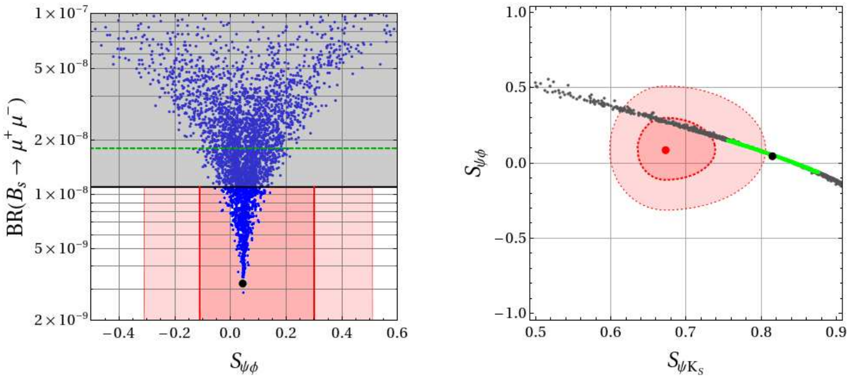
$$\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{SM}} = (3.2 \pm 0.2) \times 10^{-9}$$

bound on $\mathrm{BR}(B_s \to \mu^+\mu^-)$ strongly constrains the double penguin contributions to B mixing

- region of parameter space that minimizes the $B_s \to \mu^+\mu^-$ contraint while allowing sizable double penguin contributions to B mixing:

moderate $\tan\beta \simeq 10 - 15$,
light Higgs bosons $M_{H_2}, M_{H_3} \simeq 200 - 300\mathrm{GeV}$,
large negative mu-term $\mu \simeq -1\mathrm{TeV}$

CP Violation in B Mixing



- $\mathrm{BR}(B_s \to \mu^+\mu^-)$ severly constrains possible values for the B_s mixing phase:
  $S_{\psi\phi} \lesssim 0.15$ (still interesting in view of future LHCb sensitivity)
  (B_s mixing phase completely SM-like in the MSSM with MFV;
  WA, Buras, Paradisi '08; WA, Buras, Gori, Paradisi, Straub '09)
- Also NP contributions to the B_d mixing phase are rather restricted
- Strong constraints also from EDMs and vacuum stability

Introducing Dim. 5 Higgs-Fermion Interactions

- Dimension 5 operators that involve Higgses and Fermions are possible in the Kähler potential:

  (Dine, Seiberg, Thomas '07; Antoniadis, Dudas, Ghilencea, Tziveloglou '09)

$$\mathcal{L} \supset \frac{1}{M} \int d^4\theta \left(1 + Z + Z^\dagger + ZZ^\dagger\right) \left(\lambda_u \hat{H}_d^\dagger \hat{Q} \hat{U} + \lambda_d \hat{H}_u^\dagger \hat{Q} \hat{D} + \lambda_\ell \hat{H}_u^\dagger \hat{L} \hat{E}\right)$$

- lead to non-holomorphic Higgs fermion couplings at the tree level

$$\mathcal{L} \supset \frac{m_S}{M} (\lambda_u)_{ij}\, H_d^\dagger Q_i U_j + \frac{m_S}{M} (\lambda_d)_{ij}\, H_u^\dagger Q_i D_j + \frac{m_S}{M} (\lambda_\ell)_{ij}\, H_u^\dagger L_i E_j$$

- λ_f not necessarily aligned with the Yukawa couplings Y_f
- rotation to fermion mass eigenstates leads to
  flavor changing neutral Higgs couplings at tree level

FCNCs at Tree Level

- We assume that the wrong Higgs couplings are minimal flavor violating i.e. they can be expanded in powers of SM Yukawa couplings
  (D'Ambrosio, Giudice, Isidori, Strumia '02)

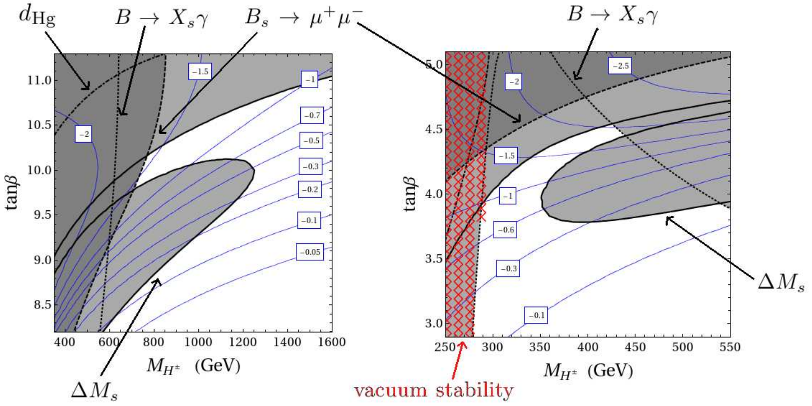
$$\frac{m_S}{M}\lambda_d = \epsilon_0 Y_d + \epsilon_1 Y_d Y_u^\dagger Y_u + \epsilon_2 Y_d Y_d^\dagger Y_d + \epsilon_3 Y_d Y_u^\dagger Y_u Y_d^\dagger Y_d + \epsilon_4 Y_d Y_d^\dagger Y_d Y_u^\dagger Y_u + \ldots$$

- FCNCs are controlled by small CKM mixing angles and the scale of the BMSSM physics 1/M
- in the MSSM the ϵ_i are loop induced

$$O(0.01) \simeq \frac{\alpha_2}{4\pi} \simeq \epsilon_i^{\text{MSSM}} \quad \leftrightarrow \quad \epsilon_i^{\text{BMSSM}} \simeq \frac{m_S}{M} \simeq O(0.1)$$

- no need for large values of $\tan\beta$ to compensate the loop suppression
- similar phenomenology as in generic 2 Higgs doublet models with MFV (ϵ_i are completely free parameters)
  (see e.g. Buras, Carlucci, Gori, Isidori '10; Buras, Isidori, Paradisi '10)

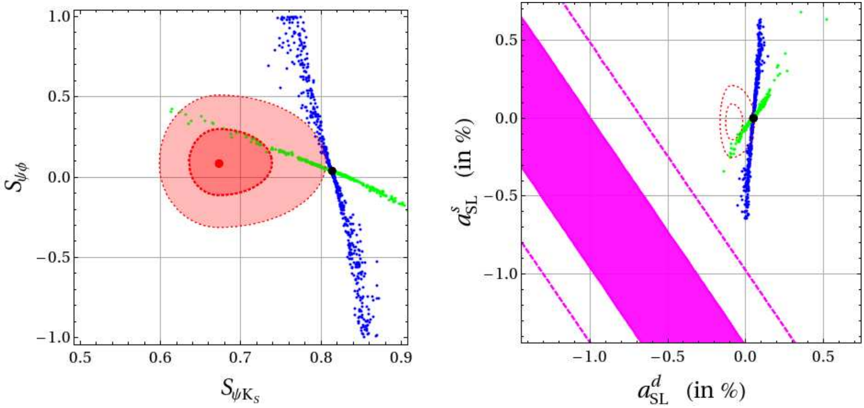
Constraints are under Control



- example scenario
  where we only consider the
  dim. 5 Kähler potential operators
- sizable effects in B_s mixing,
  small effects in B_d mixing

- example scenario
  with dim. 5 operators both in the
  Kähler and super potential
- comparable effects in B_s and B_d mixing

CP Violation in B Mixing



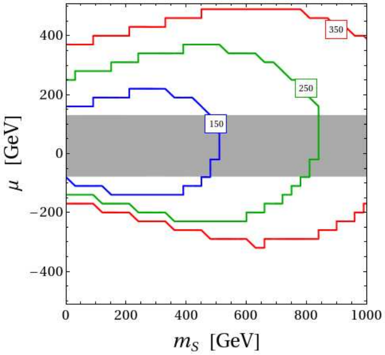
- blue points: only Kähler potential operators
  $\rightarrow$ LHCb bounds on B_s mixing phase prevent effects in B_d mixing phase
- green points: both Kähler and super potential operators;
  CP violation assumed to come from Higgs sector;
  $\rightarrow$ sizable NP phase in B_d mixing is
  in agreement with LHCb bounds on B_s mixing phase

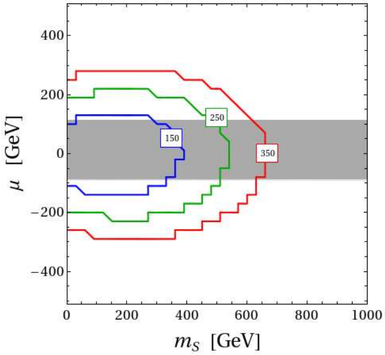
Summary

- hints towards non-zero NP phase in B_d mixing from tensions in the UT triangle: $-0.31 \lesssim \phi_d^{\mathrm{NP}} \lesssim 0$
- hints towards a large B_s mixing phase from Tevatron are not confirmed by LHCb
- still some room left for a NP phase: $-0.47 \lesssim \phi_s^{\mathrm{NP}} \lesssim 0.38$
- adding higher-dimensional operators containing Higgs fields to the MSSM can have profound impact on flavor phenomenology, in particular in B mixing and $B_s \to \mu^+\mu^-$
- dim.5 super potential operator: CPV effects in B mixing are rather restricted due to the strong bound from BR($B_s \to \mu^+\mu^-$) ($S_{\psi\phi} \lesssim 0.15$)
- dim.5 Kähler potential operators: CPV effects in B_d mixing are highly constrained by LHCb bounds on B_s mixing phase
- super + Kähler potential operators: non-standard CPV both in B_s and B_d mixing is generically possible

Back Up

Constraints from Vacuum Stability

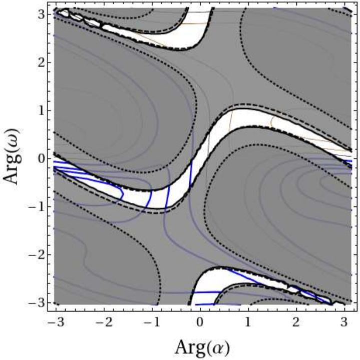




$$M = 2\text{TeV} \quad , \quad |\alpha| = |\omega| = 1$$

$$\text{Arg}(\alpha) = \text{Arg}(\omega) = 0 \text{ (left)} \quad , \quad \text{Arg}(\alpha) = \text{Arg}(\omega) = \pi/2 \text{ (right)}$$

Constraints from EDMs



$$|\omega| = 0.4 \ , \ |\alpha\omega| = 2 \ , \ M = 6 \text{ TeV}$$

$$\mu = -950\text{GeV} \ , \ m_S = 1000\text{GeV}$$

$$m_{\tilde{t}} = m_{\tilde{b}} = 500\text{GeV} \ , \ m_{\tilde{q}} = m_{\tilde{\ell}} = 4\text{TeV}$$

$$A_t = -2.5 m_{\tilde{t}} \ , \ M_3 = 3M_2 = 6M_1 = 1.2\text{TeV}$$

$$\tan\beta = 11 \ , \ M_{H^\pm} = 240\text{GeV}$$

Tree Level FCNCs

$$\mathcal{L} \supset \bar{d}_L^i \frac{m_{d_j}}{v} V_{ti}^* V_{tj} \, X_{ij} \, d_R^j \, (c_\alpha H - s_\alpha h + iA) \; + \; \bar{u}_L^i \frac{m_{d_j}}{v} V_{ij} \, Z_{ij} \, d_R^j H^+ \; + \text{h.c.}$$

$$Z_{ib} = \frac{t_\beta}{1 + \bar{\varepsilon}_6 t_\beta} \; , \qquad X_{ib} = -\frac{(\bar{\varepsilon}_2 + \bar{\varepsilon}_3) \, t_\beta^2}{(1 + \bar{\varepsilon}_5 t_\beta)(1 + \bar{\varepsilon}_6 t_\beta)}$$

$$X_{bi} = -\frac{(\bar{\varepsilon}_2 + \bar{\varepsilon}_4) \, t_\beta^2}{(1 + \bar{\varepsilon}_5 t_\beta)(1 + \bar{\varepsilon}_6 t_\beta)} \left[\frac{1 + \bar{\varepsilon}_6 t_\beta}{1 + \bar{\varepsilon}_0 t_\beta} - \frac{1 + \bar{\varepsilon}_6 t_\beta}{1 + \bar{\varepsilon}_6^* t_\beta} \, \frac{\bar{\varepsilon}_2^* + \bar{\varepsilon}_3^*}{\bar{\varepsilon}_2 + \bar{\varepsilon}_4} \, \frac{(\bar{\varepsilon}_1 + \bar{\varepsilon}_3) t_\beta}{1 + \bar{\varepsilon}_0 t_\beta} \right]$$

$$\bar{\varepsilon}_0 = \epsilon_0 \;\; , \quad \bar{\varepsilon}_1 = y_b^2 \epsilon_1 \;\; , \quad \bar{\varepsilon}_3 = y_t^2 y_b^2 \epsilon_3 \;\; , \quad \bar{\varepsilon}_2 = y_t^2 \epsilon_1 \;\; , \quad \bar{\varepsilon}_4 = y_t^2 y_b^2 \epsilon_4$$

$$\bar{\varepsilon}_5 = \bar{\varepsilon}_0 + \bar{\varepsilon}_1 + \bar{\varepsilon}_2 + \bar{\varepsilon}_3 + \bar{\varepsilon}_4 \;\; , \quad \bar{\varepsilon}_6 = \bar{\varepsilon}_0 + \bar{\varepsilon}_1 + \bar{\varepsilon}_4$$